

PREDICTIONS OF SPRAY COMBUSTION INTERACTIONS*

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Measurements were completed in dilute particle-laden jets, nonevaporating sprays and evaporating sprays injected into a still air environment. The flows are stationary, turbulent, axisymmetric and conform to the boundary layer approximations while having well-defined initial and boundary conditions--to facilitate use of the data for evaluation of analysis of the processes. Mean particle (drop) sizes were in the range 2-210 microns over the entire data base. The following measurements were made (as appropriate for the flow): mean and fluctuating phase velocities; mean particle mass flux; particle size; and mean gas-phase Reynolds stress, composition and temperature. Three models of the processes, typical of current practice, were evaluated using both existing and the new data: (1) a locally homogeneous flow (LHF) model, where interphase transport rates are assumed to be infinitely fast; (2) a deterministic separated flow (DSF) model where finite interphase transport rates were considered but effects of turbulence/drop interactions were ignored; and (3) a stochastic separated flow (SSF) model where effects of finite interphase transport rates and turbulent fluctuations were treated using random sampling for turbulence properties in conjunction with random-walk computations for particle (drop) motion. All three models used a $k-\epsilon-g$ model for the continuous phase--which performed well in earlier studies of single-phase jets. The LHF and DSF models did not provide very satisfactory predictions over the present data base. In contrast, the SSF model generally provided good predictions and appears to be an attractive approach for treating nonlinear interphase transport processes in turbulent flows containing particles (drops). Current work is considering measurements and analysis of combusting sprays.

INTRODUCTION

The main objective of this investigation was to complete measurements of the structure of dilute particle-laden jets and sprays in order to support development of analysis of these processes. Test configurations involved injection into still air, yielding stationary, turbulent, axisymmetric flows, having well-defined initial and boundary conditions, which conform to the boundary layer approximations. The complexity of interphase transport was increased systematically, considering particle-laden jets, nonevaporating sprays, evaporating sprays and combusting sprays, in turn. In order to insure that appropriate measurements were made, model development was also

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undertaken--considering methods typical of current practice. The results of the study have application to the development of rational design methods for aircraft combustion chambers as well as other devices involving spray evaporation and combustion.

The following description of the study is brief. Full details and a complete tabulation of data can be found in papers, reports and theses completed under the study (refs. 1-11). Studies of sprays and particle-laden jets have recently been reviewed by one of us (refs. 12 and 13) and this discussion will not be repeated here. Based on these reviews, and others cited therein, there is general agreement that a most pressing need for gaining a better understanding of spray processes is the creation of a well-defined set of measurements of the structure of these flows--motivating the present investigation.

In the following, experimental and theoretical methods are described first of all. This is followed by a discussion of results already completed for particle-laden jets, nonevaporating sprays and evaporating sprays. The paper concludes with a brief discussion of current work being undertaken in combusting sprays.

EXPERIMENTAL METHODS

Test Apparatus

The same test configuration was used for the particle-laden jets and nonevaporating and evaporating sprays, cf., figure 1. The injector was directed vertically downward within a screened enclosure. The injector and enclosure were traversed, since optical instrumentation was mounted rigidly. An exhaust system was used, to prevent recirculation of fine particles, however, its operation had negligible influence on flow properties at the measuring station.

Test conditions are summarized in tables I and II for the particle-laden jets and the sprays, respectively. In each case, an air jet from the same injector was also tested, in order to establish test procedures by comparison with existing measurements. The particle-laden jets were essentially monodisperse with particle diameters in the range 79-207 microns while the sprays had Sauter mean diameters (SMD) in the range 30-87 microns. In general, measurements were confined to dilute regions of the flow where void fractions exceeded 99%. All the flows were turbulent, with initial jet Reynolds numbers exceeding 10000.

Instrumentation

A single-channel laser-Doppler anemometer (LDA) was used to measure mean and fluctuating velocities of the continuous phase. High concentrations of seeding particles were used to avoid biasing due to flow particles (in the following, "particle" is used to represent "drop" unless the distinction is important). Data densities were high so that measured quantities could be time-averaged. The LDA was also used to obtain mean and fluctuating particle

velocities in the particle-laden jets--after terminating the flow of seeding particles.

Double-flash photography was used to check LDA measurements of particle properties in particle-laden jets and to measure drop size and velocity correlations in the sprays. Drop size distributions obtained in this manner were corrected for depth-of-focus bias. Drop size distributions were also measured by slide impaction--corrected for Reynolds number bias. Finally, a Malvern particle sizer, which operates by Fraunhofer diffraction of a laser beam, was used to monitor drop size distributions in the nonevaporating sprays, however, this instrument was ineffective in the evaporating sprays due to beam steering by gas-phase density gradients.

Mean particle mass flux and liquid flux in the nonevaporating sprays were measured by isokinetic sampling at the mean gas velocity using a diverging probe. Isokinetic sampling with a heated probe, followed by analysis with a gas chromatograph, was used to measure mean total Freon-11 concentrations in the evaporating sprays. A shielded fine wire (25 micron diameter) thermocouple was used to measure mean gas-phase temperatures in the evaporating sprays. An impact plate was used to measure injector thrust.

Measurements in the particle-laden jets were conducted for $x/d = 1-50$, where x is distance from the injector and d is the injector diameter. Adequate spatial resolution for the sprays could only be achieved for $x/d = 50$ with measurements extending to $x/d = 500-600$, due to the small exit diameter of the injector. For all test conditions, baseline calibration tests were conducted to establish predictions of transport rates to individual particles (drops).

THEORETICAL METHODS

General Description

Three models were considered: (1) a locally homogeneous flow (LHF) model where interphase transport rates are assumed to be infinitely fast, (2) a deterministic separated flow (DSF) model where finite interphase transport rates were considered but effects of turbulence/drop interactions were ignored; and (3) a stochastic separated flow (SSF) model where finite interphase transport rates and interactions between drops and turbulent fluctuations were treated using random sampling for turbulence properties in conjunction with random-walk computations for particle (drop) motion. A $k-\epsilon-g$ model was used to find properties of the continuous phase for all three models, since this approach provided good structure predictions for single-phase jets (ref. 12). The test conditions correspond to steady, turbulent, axisymmetric boundary layer flows having low Mach numbers where effects of viscous dissipation of the mean flow and radiation are small. Other assumptions vary for the LHF, DSF and SSF models and will be treated separately in the following.

LHF Model

The LHF approximation implies that both phases have the same velocity and are in local thermodynamic equilibrium at each point in the flow--which is only

exact for infinitely-small particles. Therefore, the flow corresponds to a single-phase fluid with an unusual equation of state due to the presence of particles. The analysis employed Favre (mass)-averaged governing equations in conjunction with the conserved-scalar formalism of Bilger (ref. 14). This procedure eliminates ad hoc neglect of density velocity correlations and effects of buoyancy in the governing equations for turbulence quantities. The relationship between scalar properties and mixture fraction, needed by this approach, followed past practice in this laboratory (ref. 13). The LHF model does not require detailed information concerning initial drop sizes and velocities; therefore, LHF calculations were begun at the injector exit.

DSF Model

Both separated flow models adopt the features of the LHF model for the gas phase. The dispersed phase was treated by solving Lagrangian equations of motion for the particles and then computing source terms for interphase transport which appear in the governing equations for the gas phase. This involves dividing the particles into a number of groups at the initial condition and then computing their subsequent motion.

Void fractions in the region of computation always exceeded 99%; therefore, the dispersed phase volume, particle collisions and effects of adjacent particles on interphase transport rates could be ignored with little error. Ambient conditions for particles were taken to be local mean gas properties; therefore, effects of turbulent fluctuations on interphase transport, turbulent dispersion and turbulence modulation were ignored--typical of most current spray models (ref. 13). Effects of varying local ambient conditions, however, were considered.

SSF Model

The SSF model treats turbulence/drop interactions by computing drop trajectories as they move away from the injector and encounter a succession of turbulent eddies--using Monte Carlo methods. Properties within each eddy are assumed to be uniform, but to change in a random fashion from one eddy to the next. Trajectory calculations are the same as the DSF model, except that instantaneous eddy properties replace mean gas properties. Eddy properties are found by making a random selection from the probability density functions (PDF) of velocity and mixture fraction. A drop is assumed to interact with an eddy as long as its relative displacement with respect to the eddy is less than a characteristic eddy size and its time of interaction is less than a characteristic eddy lifetime. All these parameters are directly found from the k- ϵ -g computations.

RESULTS AND DISCUSSION

Particle-Laden Jets

Initial evaluation of the models was undertaken using existing measurements in the literature (refs. 1,2). It was found that the LHF model

was only effective for flows containing tracer-sized particles, that the DSF model was not effective for any flow, and that the SSF model yielded encouraging predictions of flow structure and particle dispersion. The evaluation was not definitive, however, due to uncertainties in initial conditions for existing measurements.

Initial conditions were fully defined for present tests with particle-laden jets--removing earlier limitations. Typical structure measurements and predictions are illustrated in figures 2-6 (u and v are axial and radial velocities, G is particle mass flux and subscripts o and c denote initial and centerline conditions). In figure 2, the agreement between predicted and measured velocities in the gas jet is good--establishing a baseline for the work. The LHF and SSF predictions are nearly identical and are also in good agreement with measurements. Particle velocities, illustrated in figure 3, exhibit more significant effects of the model. The LHF approach underestimates particle velocities since effects of slip are ignored while the SSF model yields good results. Results for centerline particle mass flux, illustrated in figure 4, are similar.

Radial variations of gas and particle properties are illustrated in figures 5 and 6. All gas-phase predictions are similar and are in reasonably good agreement with measurements, however, only the SSF model yields good predictions of mean and fluctuating particle properties. The DSF model underestimates particle spread rates, since effects of turbulent dispersion are ignored while the LHF model overestimates spread rates since slip is ignored.

The flows were too dilute to test predictions of turbulence modulation by the SSF model. Sensitivity studies showed that predictions were most sensitive to initial particle properties.

Nonevaporating Sprays

A portion of the results for nonevaporating sprays is illustrated in figures 7-12. In this case, the LHF predictions are initiated at the injector exit while the separated flow model predictions are initiated at $x/d = 50$, where adequate initial conditions could be measured. Results for mean gas velocities and liquid fluxes along the centerline (figures 7 and 8) are similar: the SSF model yields good predictions while the LHF model overestimates the rate of development of the flow. SMD variation along the axis is illustrated in figure 9. The SMD increases gradually along the axis, due to turbulent drop dispersion. The SSF model correctly predicts this trend while the DSF model yields an opposite trend since turbulent dispersion is ignored.

Radial profiles of mean liquid flux are illustrated in figure 10. Turbulent dispersion of drops causes these flows to extend beyond $r/x = 0.2$, which is the usual boundary for a single-phase jet. The SSF model correctly predicts this trend--which is an encouraging finding--while the other models are unsatisfactory.

Radial profiles of mean drop velocity for the case 1 spray and the SMD of both sprays are illustrated in figures 11 and 12. The correlation between drop

size and velocity is predicted reasonably well by the SSF model--as is the SMD variation.

Turbulence modulation was again not an important factor in these sprays and could not be adequately evaluated. Specification of initial drop properties was found to have the greatest influence on predictions.

Evaporating Sprays

A portion of the findings for evaporating sprays is illustrated in figures 13-16. Trends are qualitatively similar to results for nonevaporating sprays, however, differences between the models are somewhat reduced due to effects of drop evaporation.

Combusting Sprays

Current tests and analysis are extending results to combusting sprays. Initial tests are limited to dilute conditions where the flame is primarily fueled by gas (methane) with a monodisperse stream of drops in coflow with the gas fuel. This system simplifies measurements and the presentation of results and allows greater concentration on the interesting fundamental problem of drop/combusting turbulent flow interactions. Subsequent work will consider flames fully fueled with polydisperse sprays.

CONCLUSIONS

Major conclusions are: (1) the SSF model provides a useful approach for treating turbulence/drop interactions in particle-laden flows and sprays with minimal empiricism and a capability to treat nonlinear effects; (2) the LHF model is a useful simplification for very well-atomized sprays (particle/drop size less than 10 μm) but effects of slip are important for most practical sprays; and (3) the DSF model was not effective for any of the flows examined here, since effects of turbulent particle dispersion and effects of turbulent fluctuations on interphase transport rates are important in most practical sprays.

Specification of initial conditions is the most critical aspect of spray structure predictions. Effects of turbulence modulation were small for present flows, and current SSF model treatment of this phenomenon could not be evaluated decisively. Current work is extending the data base and the model evaluation to dilute combusting sprays.

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TABLE I.-SUMMARY OF PARTICLE-LADEN JET TEST CONDITIONS

Flow	Air Jet	Dilute Particle-Laden Jets			
		1	2	3	4
Case	--	1	2	3	4
SMD (microns)	--	79	119	119	207
Loading Ratio	--	0.20	0.20	0.66	0.66
<u>Injector Exit Conditions:^b</u>					
Velocity (m/s)					
Air	32.1	26.1	29.9	25.2	25.3
Particle	--	24.1	24.2	21.9	18.5
Particle Mass Flux (kg/m ² s)	--	6.1	6.5	18.9	19.0

^aInjector exit diameter of 10.9 mm; particle density 2620 kg/m³.

^bAt flow centerline.

TABLE II.-SUMMARY OF SPRAY TEST CONDITIONS^a

Flow	Air Jet	Nonevaporating Sprays		Evaporating Sprays	
		1	2	1	2
Case	--	1	2	1	2
Injected Fluid	air	air/oil ^b	air/oil ^b	air/Freon-11	air/Freon-11
Flow Rates, mg/s					
Gas	338	338	216	188	120
Liquid	0	600	1400	1450	1894
Loading Ratio	0	1.8	6.5	7.7	15.8
Jet Momentum, mN	120	137	70	106	60
Initial Velocity, m/s ^c	175	146	43	65	30
Reynolds number ^c	26000	30000	24000	41000	36000
SMD, microns	--	30 ^d	87 ^d	31 ^e	58 ^e
Spray Angle, deg.	--	30	33	27	29

^aSpraying systems air-atomizing injector, 1.2 mm exit diameter.

^bVacuum pump oil, Sargent-Welch, Cat. No. 1407K25.

^cAssuming LHF with air viscosity for Reynolds number.

^dMeasured with Malvern, Model 2200 Particle Sizer @ $x/d = 12.6$.

^eMeasured by slide impaction at $x/d = 50$.

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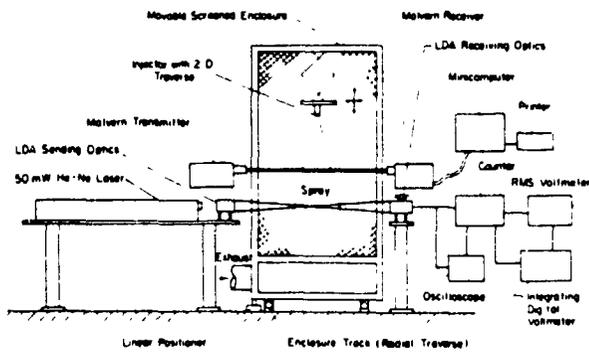


Figure 1.
SKETCH OF THE EXPERIMENTAL APPARATUS

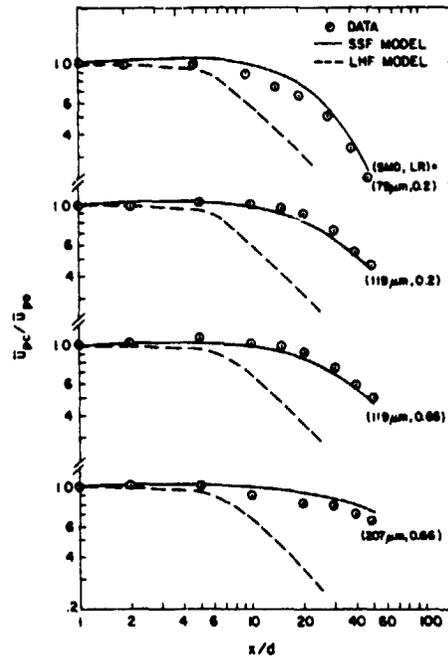


Figure 3.
CENTERLINE MEAN PARTICLE VELOCITY
IN PARTICLE-LADEN JETS

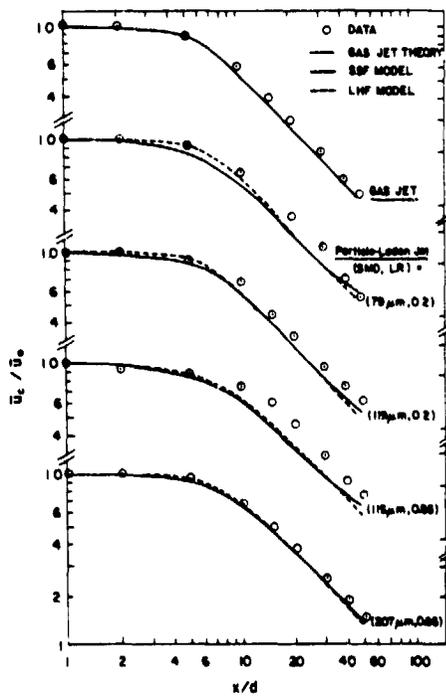


Figure 2.
CENTERLINE MEAN GAS-PHASE VELOCITY
IN PARTICLE-LADEN JETS

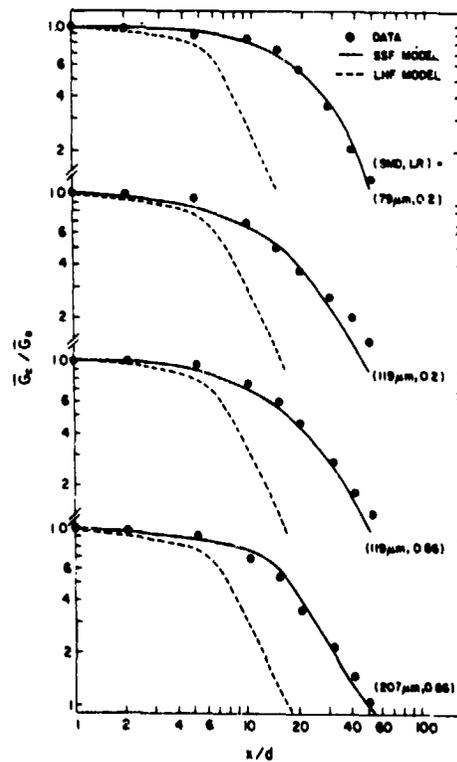


Figure 4.
CENTERLINE MEAN PARTICLE MASS FLUX
IN PARTICLE-LADEN JETS

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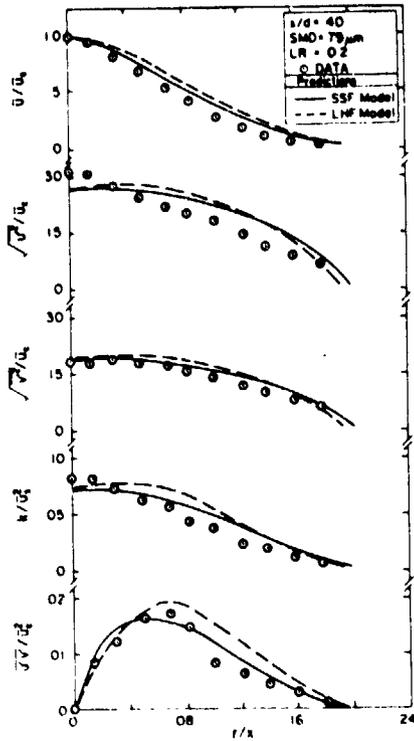


Figure 5.
GAS-PHASE PROPERTIES AT $x/d = 40$
FOR CASE 1 PARTICLE-LADEN JET

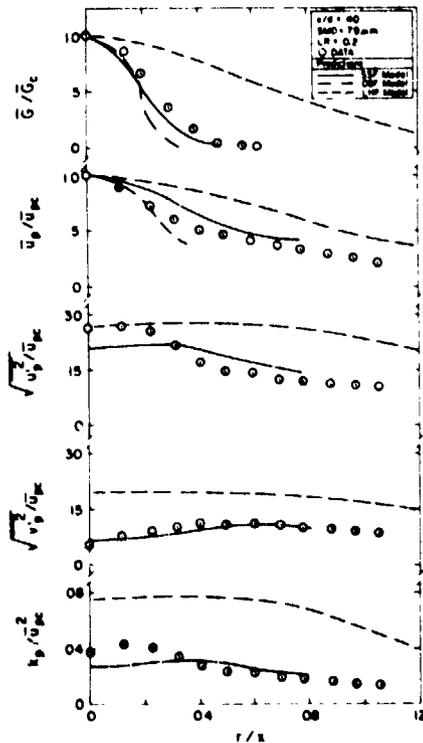


Figure 6
PARTICLE PROPERTIES AT $x/d = 40$
FOR CASE 1 PARTICLE-LADEN JET

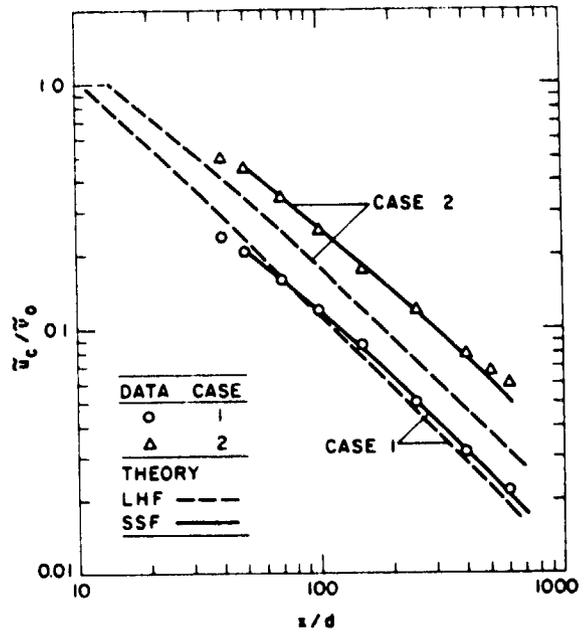


Figure 7
CENTERLINE MEAN GAS-PHASE VELOCITIES
FOR NONEVAPORATING SPRAYS

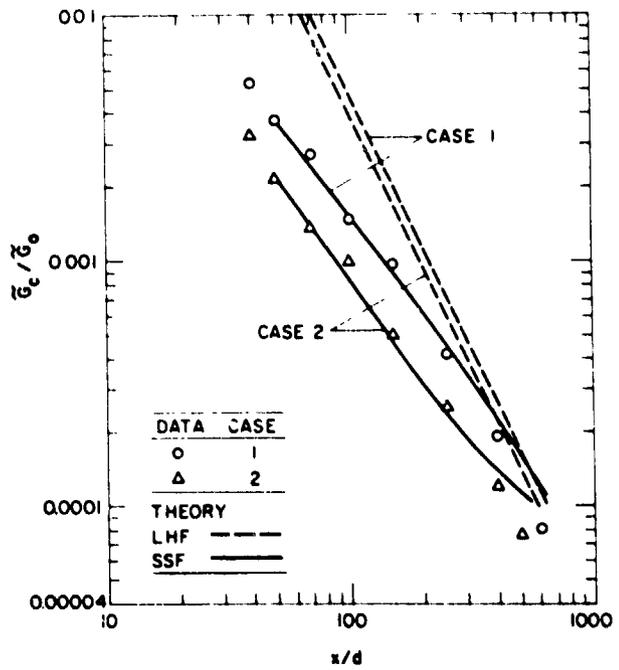


Figure 8
CENTERLINE MEAN LIQUID FLUX
FOR NONEVAPORATING SPRAYS

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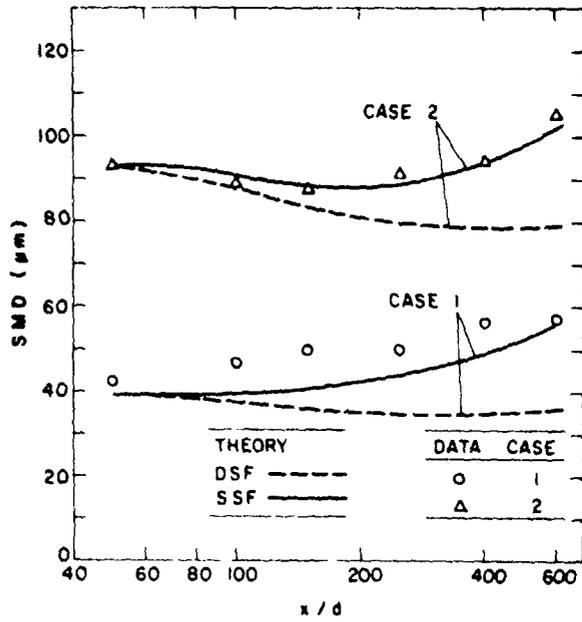


Figure 9
CENTERLINE SMD
FOR NONEVAPORATING SPRAYS

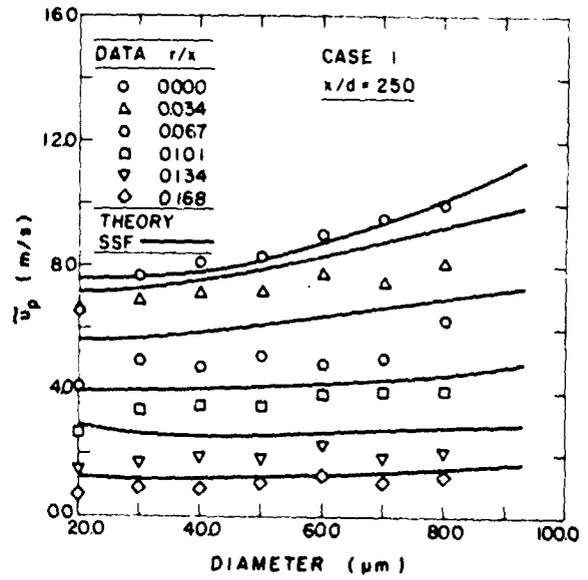


Figure 11
MEAN DROP VELOCITIES AT $x/d = 250$
FOR CASE 1 NONEVAPORATING SPRAY

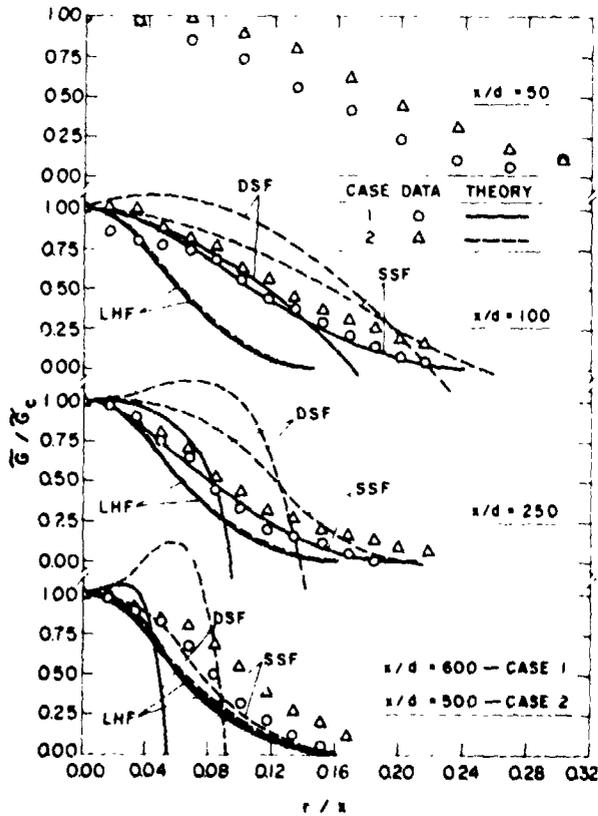


Figure 10
RADIAL PROFILES OF MEAN LIQUID FLUX
IN NONEVAPORATING SPRAYS

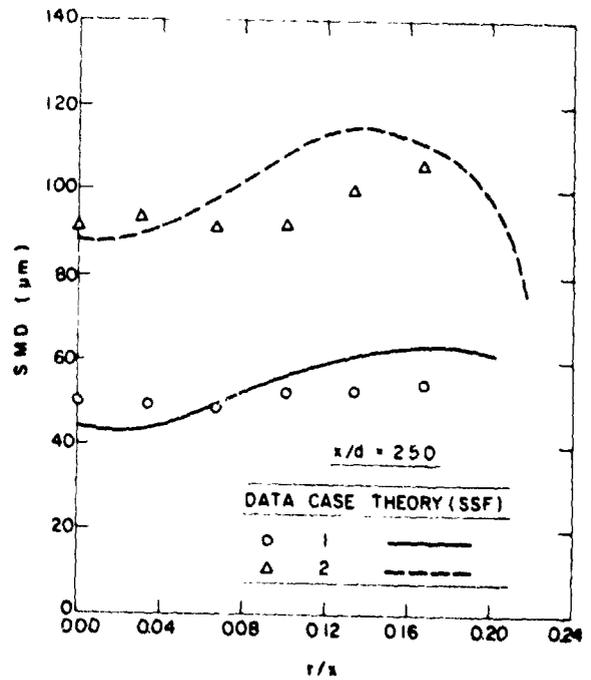


Figure 12
SMD AT $x/d = 250$
FOR NONEVAPORATING SPRAYS

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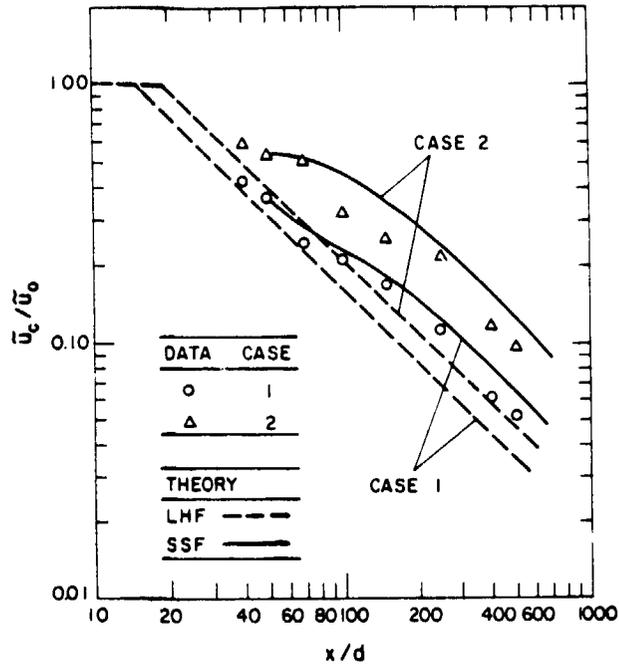


Figure 13
CENTERLINE MEAN GAS VELOCITIES
FOR EVAPORATING SPRAYS

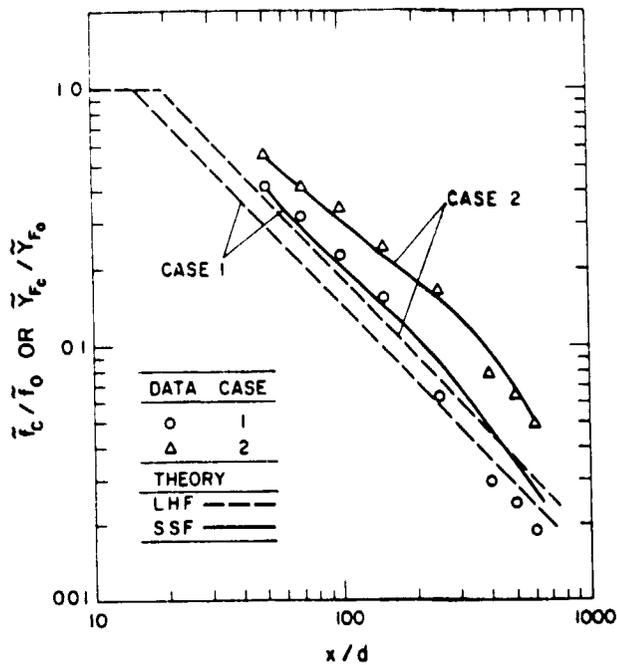


Figure 14
CENTERLINE MEAN FREON-11
CONCENTRATION FOR EVAPORATING SPRAYS

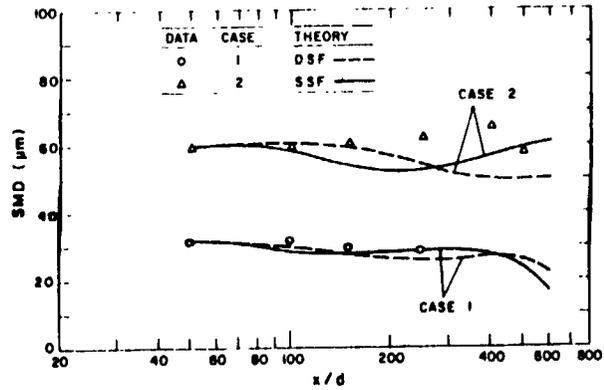


Figure 15
CENTERLINE SMD FOR EVAPORATING SPRAYS

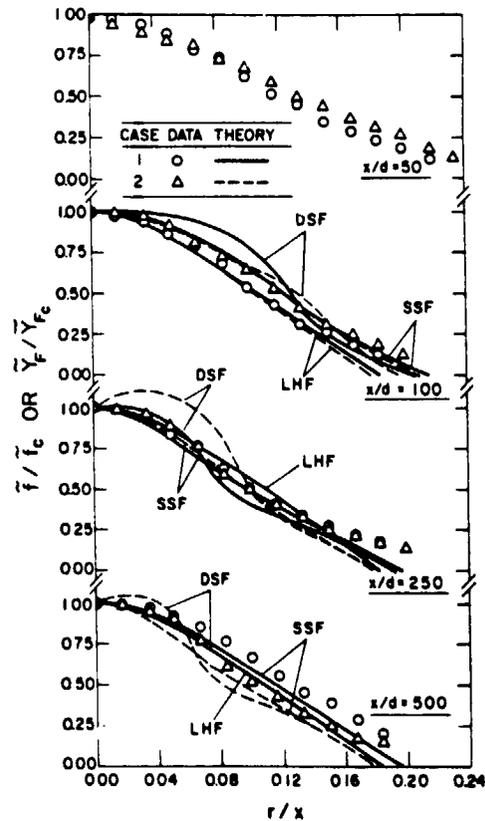


Figure 16
RADIAL PROFILES OF MEAN FREON-11
CONCENTRATION FOR EVAPORATING SPRAYS